PROBING THE DENSITIES OF GAP STATES IN INTRINSIC a-Si:H USING SPACE CHARGE LIMITED CURRENTS OF ELECTRONS AND HOLES

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ABSTRACT

Space charge limited currents of holes in intrinsic hydrogenated amorphous silicon (a-Si:H) have been obtained using novel p+-intrinsic-p÷ (p-i-p) structures. The presence of these hole space charge limited currents is verified from their temperature dependence and their dependence on a wide range of intrinsic layer thickness. The carrier transport and space charge limited currents in the p-i-p structures are compared with those of n-i-n structures and the results are discussed in terms of a self consistent density of states in the gap.

INTRODUCTION

Single carrier space charge limited currents (SCLC) have been extensively studied in hydrogenated amorphous silicon (a-Si:H). They have been applied by several groups to determine the densities of states (DOS) in the forbidden gap[1,2,3,4,5] above the fermi level, E\text{f}. But, little or no work has been reported on the DOS below E\text{f} based on SCLC measurements. In the studies on the DOS above midgap, electron SCLC are established through the use of n-i-n structures. The corresponding study of the DOS below E\text{f} requires structures which exhibit single carrier hole transport so that the SCLC move E\text{f} down through the DOS below E\text{f}. Thus far, single carrier hole SCLC in a-Si:H have only been reported for lightly doped p-type material by using p-i-p structures[6]. The DOS derived from such measurements, however, does not reflect the gap states present in intrinsic a-Si:H since it is well known that doping introduces a large number of defects. We have investigated the transport of holes in intrinsic undoped a-Si:H by using p-i-p structures and present data showing hole SCLC as confirmed by measurements at different temperatures and on structures of varying thickness. These results are discussed in terms of a self consistent DOS.

EXPERIMENTAL PROCEDURE

The a-Si:H films were deposited using a plasma assisted chemical vapor deposition (PACVD) process under conditions previously described[7]. Both the n-i-n and the p-i-p structures were deposited on substrates of conducting tin oxide on glass. The p type doped layers were 300 Å thick and intrinsic layers were from 0.5 μm to 3.0 μm thick. Several corresponding n-i-n structures were also deposited in order to compare the carrier transport with that in the p-i-p structures. Semi-transparent metal contacts of area 2 mm were then evaporated on these structures. Due to the thinness of the doped layers, lateral conduction and edge currents were negligible which was verified by scribing around individual dots and observing no changes in the current density-versus-voltage (J-V) characteristics. Sufficient time was given for the currents to equilibrate during each measurement. In the p-i-p structures, the current typically decreased for 15 to 30 seconds to a quasi-equilibrium value which then remained
essentially unchanged. The temperature measurements were carried out in a vacuum of $1 \times 10^{-4}$ torr where all the measurements, except those related to light soaking, were carried out after annealing at 190°C for 2 hrs. The light soaking was done with AM1 light passed through an IR filter to reduce heating effects.

RESULTS AND DISCUSSION

Due to the asymmetry in the DOS around the middle of the gap in a-Si:H, significant differences are expected between the electron currents observed in n-i-n structures and hole currents observed in p-i-p structures. It can be seen in Fig. 1 that the currents in an n-i-n structure are much larger than those in an equivalent p-i-p structure. The much larger currents in the n-i-n structure are attributed to the band bending created by the contact potentials[8]. The much lower currents in the p-i-p structure reflect a conductivity comparable to or lower than that of a bulk intrinsic layer and indicate that the Fermi level is close to midgap. This implies that the contact effects in the p-i-p structures are much smaller than in the n-i-n structures. This is due to the large DOS below midgap which rapidly screens the contact potential. Thus, it is more difficult to shift $E_F$ towards the valence band than towards the conduction band.

Differences in carrier transport are further reflected in the changes of the dark currents before and after extended exposure to light. There is a striking difference between the two structures in both the magnitude and the direction of the current changes in the low voltage regimes. The decrease in the n-i-n conductivity is consistent with an increase in the defect density near midgap which leads to a lowering of $E_F$. In the low voltage regime of the p-i-p structure, there is a slight increase in the conductivity. This is consistent with a lowering of $E_F$ and a subsequent increase in the free hole concentration. An alternative explanation for the currents in the low voltage regime of the p-i-p structure is that, since $E_F$ is close to midgap, there is a significant contribution from generation currents such as exist in reverse biased p-i-n structures. The conductivity increase after light soaking could then be due to higher generation currents resulting from light induced defects near midgap.

The nature of the p-i-p currents was further investigated using structures of different thickness. Fig. 2 shows the J-V characteristics of four p-i-p structures of thickness 0.5 μm, 1.0 μm, 1.8 μm, and 2.9 μm. In all cases, there is a slow increase at low voltages which then turns into a region of high power dependence at high voltages. It can be seen that in the low voltage regimes, not all the structures exhibit a linear dependence on voltage and that the deviation from this increases with thickness. This trend is consistent with carrier generation in the bulk i-layer. The generation currents appear to be comparable to the drift current of the 1 μm structure so they tend to reduce the slope of the J-V characteristic in the thicker samples. These generation currents have an important effect on measured values of activation energies of thicker p-i-p structures and thin p-i-n-p structures.

Since the hole drift currents at low voltages dominate conduction in the 0.5 μm structure, its J-V characteristics were measured at
different temperatures to obtain the activation energy of hole conduction. The results are presented in Fig. 3 where for all temperatures there is a linear regime which subsequently turns into a high power dependence. The point at which this transition occurs moves to higher voltages with increasing temperature which is consistent with an increase in the intrinsic hole concentration. For comparison, the temperature dependence of the J-V characteristic for the n-i-n structure of Fig. 1 is shown in Fig. 4. Again, the transition to the high power voltage dependence moves to higher values with temperature.

The activation energies obtained from the ohmic regimes of the p-i-p structure in Fig. 3 and the n-i-n structure of Fig. 4 are 1.0 eV and 0.6 eV respectively. The activation energy of the n-i-n structure reflects the effects of the n+ contacts and low DOS above mid-gap which places $E_F$ close to the conduction band. Without any such band bending, the activation energy would be determined by $E_F$ in the bulk a-Si:H which in high quality materials is near mid-gap. The activation energy of 0.9 eV on an equivalent coplanar structure is consistent with the 1.9 eV mobility gap of a-Si:H[9] and its slightly n-type nature. The activation energy of the p-i-$x$structure, on the other hand, is greater than the coplanar, but still close to half of the bandgap. This activation energy is associated with hole conduction and reflects the distance of $E_F$ from the valence band. This large value clearly indicates that $E_F$, even in thin p-i-p structures, is pinned near midgap in contrast to the n-i-n structures.

The results presented in Figs. 2 and 3 show that for thin (< 1 μm) p-i-p structures, the drift current of holes injected from the p contacts can be observed even at low applied voltages. For thicker p-i-p structures, the generation currents can be comparable to the hole drift currents. Nevertheless, at
sufficiently high bias, purely hole transport can still be observed since the generation currents rapidly saturate with voltage. A confirmation of this is provided by the scaling law for SCLC [10,11] which relates current $J$, voltage $V$, and sample thickness $L$ by $J/L = f(V/L^2)$. This relation differentiates SCLC from other high field current mechanisms such as avalanche breakdown, device punchthrough, or the Frenkel effect. The results of Fig. 2 are replotted in Fig. 5 as $J/L$ versus $V/L^2$.

Fig. 3. Temperature Dependence of p-i-p J-V Characteristics

Fig. 4. Temperature Dependence of n-i-n J-V Characteristics

Fig. 5. Scaling Law for p-i-p samples of varying thickness.

Fig. 6. Proposed DOS
according to the scaling law. The excellent agreement at high voltages obtained with four different thicknesses whose \( L \) ratio covered a range of up to 35, confirms the presence of SCLC in the structures. The ability to obtain SCLC of holes offers a means of probing the DOS below \( E_f \) in intrinsic a-Si:H.

The large differences between the currents in the n-i-n and p-i-p structures and yet the onset of SCLC at similar voltages seen in Fig. 1 can be explained by the DOS shown in Fig. 6. This DOS has a region of low density at and above the middle of the gap and a higher DOS close to the valence band tails. The important factors in determining the shifts in \( E_f \) in the n-i-n and p-i-p structures is the location of these defects relative to midgap. The low DOS above midgap offers minimal screening for the contact potential in the n-i-n structure and \( E_f \) can readily move until it approaches the conduction band tails. This is why the fermi level is significantly displaced from its bulk value in the n-i-n structures. On the other hand, the defect states close to the valence band tails extend close to midgap which causes much more efficient pinning of \( E_f \) in the p-i-p structures. The consequence of this is that much thinner i-layers screen the effects of the p-contacts and \( E_f \) remains close to the bulk value. This is borne out by thermal equilibrium calculations of the band diagrams for n-i-n and p-i-p structures of different thicknesses whose i-layer has the proposed DOS. The calculated values using detailed numerical calculations[12] are presented in Table 1 where the n-i-n structures show that \( E_f \) in the middle of the structures shifts with thickness and reaches bulk values only for thicknesses greater than 4 \( \mu \text{m} \). On the other hand, \( E_f \) remains pinned near midgap for the p-i-p structures of the same thickness. The hole SCLC reported here are also consistent with such a distribution of states and detailed modelling based on first principles numerical calculations is being carried out on both n-i-n and p-i-p structures to accurately evaluate the DOS above and below the fermi level.

**CONCLUSIONS**

The transport of holes in intrinsic a-Si:H has been investigated by using novel p-i-p structures and the presence of hole SCLC has been demonstrated. The distinct differences observed in the J-V characteristics and activation energies of n-i-n and p-i-p structures can be explained by the difference in the DOS above and below \( E_f \). The absence of any significant change in the activation energy of the p-i-p samples with thickness and the high values of the activation energies are attributed to the relatively large density of states just below \( E_f \). These defect states rapidly screen the p contacts and, thus allow \( E_f \) to reach bulk values even in structures less than 1 \( \mu \text{m} \) thick. The ability to measure the hole SCLC offers a method of probing the DOS below \( E_f \) in intrinsic a-Si:H and by using further detailed analysis, their densities can be accurately determined.
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REFERENCES